Condition monitoring and fault diagnosis of diesel engines using instantaneous angular speed analysis ☆

Tian Ran Lin [1, 2], Andy CC Tan [2], Lin Ma [1, 2] and Joseph Mathew [1]

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[1] CRC for Infrastructure and Engineering Asset Management,

[2] School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, 2 George Street, Brisbane, QLD 4001 Australia

Corresponding author:

Tian Ran Lin, School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, 2 George Street, Brisbane, QLD 4001 Australia
Email: trlin@qut.edu.au

Abstract

Continuous monitoring of diesel engine performance is critical for early detection of fault developments in an engine before they materialize into a functional failure. Instantaneous crank angular speed (IAS) analysis is one of a few non-intrusive condition monitoring techniques that can be utilized for such a task. Furthermore, the technique is more suitable for mass industry deployments than other non-intrusive methods such as vibration and acoustic emission techniques due to the low instrumentation cost, smaller data size and robust signal clarity since IAS is not affected by noise and other diesel engine operation conditions. In this experimental study, IAS analysis was employed for engine loading estimation and fault diagnosis of a 4-stroke 4-cylinder diesel engine in a laboratory. It was shown that IAS analysis can provide useful information about engine speed variation caused by changing piston momentum and crankshaft acceleration during the engine combustion process. It was also found that the major order component of the IAS spectra directly associated with the engine firing frequency (at twice the mean shaft rotating speed) can be utilized to estimate engine loading condition regardless of whether the engine is operating at healthy condition or with faults. The amplitude of this order component follows a distinctive exponential curve as the loading condition changes. A mathematical relationship was then established to estimate the engine power output based on the amplitude of this order component of the IAS spectrum. It was further illustrated that IAS technique can be employed for the detection of a simulated exhaust valve fault in this study.

Keywords:

Condition monitoring, Instantaneous angular speed analysis, Order analysis, Diesel engine performance, Fault diagnosis

Introduction

Diesel engines are one of the most critical classes of machinery in industry today. Unpredicted failures of diesel engines can cause dire consequences. It is thus essential to mitigate unpredicted engine failures to ensure continuing operation and optimum engine performance. Engine failures could be caused either by combustion related subsystems, such as the fuel injection system, the cylinder/piston system, the inlet and outlet valve system, or by non-combustion related subsystems including all auxiliary devices such as turbochargers, gears, bearings and electronic control units. Faults developed in combustion related subsystems can directly affect the combustion process and engine performance. Engine misfire, knocking, insufficient power output, poor fuel efficiency, excessive exhaust smoke, excessive noise and vibration are some of the most typical fault symptoms of a diesel engine. To minimize or to prevent the occurrence of unpredicted engine failures, the operating state and health of a diesel engine needs to be monitored continually so that a fault symptom and its root cause could be diagnosed and dealt with at the early stage before it becomes a functional failure.

Instantaneous crank angular speed and in-cylinder pressure methods are two commonly employed condition monitoring techniques for engine performance monitoring and combustion related fault detection. In-cylinder pressure technique can provide a direct indication of engine performance and the state of the combustion process. However, applications of the technique are restrained by the intrusive nature of the method. Furthermore, in-cylinder pressure measurement is a localized technique which can only detect or monitor the combustion process of the cylinder with an attached pressure sensor. Prompted by the rapid development of data acquisition hardware and signal processing techniques over the last decade or two, a non intrusive Instantaneous Angular Speed (IAS) measurement is gaining wide acceptance for condition monitoring and fault detection of rotating machinery. For instance, the IAS technique was successfully employed for torsional vibration analysis [1, 2], condition monitoring of gear transmission [2-5], condition monitoring and fault detection of diesel engines [6-9], condition monitoring of electric motors [10] and roller element bearing fault detection [11]. The IAS technique can also be employed to monitor engine performance as the variation of crank angular speed is directly correlated to the total gas pressure torque produced by the combustion process.

In the application of IAS for fault detection and diagnosis of diesel engines, Yang et al [6] presented a simple two-degree-of-freedom dynamical system to simulate instantaneous angular speed fluctuation of a four-stroke four-cylinder diesel engine. They found that the instantaneous angular speed is largely affected by the tangential force induced by the gas pressure and the vertical imbalance inertial force produced by piston acceleration/deceleration of all the cylinders. They further illustrated that the fluctuation of IAS can be utilized to detect engine combustion related faults such as those affecting the combustion pressure of the cylinders, i.e., fuel or exhaust valve leakages. Charles et al [7] extended the IAS technique further for condition monitoring and fault diagnosis of diesel engines with large number of cylinders. By presenting the IAS waveform in a polar coordinate system, they demonstrated that the IAS waveform can be utilized to detect and identify the faulty (misfiring) cylinder of two relatively large multi-cylinder (16 and 20 cylinders, respectively) engines. Taraza et al [8] investigated the amplitude change of order components of IAS waveforms of two diesel engines and correlated the amplitude of the lowest major harmonic order (order 2 for a 4-cylinder engine and order 3 for a six-cylinder engine) of IAS spectra to that of the gas pressure torque produced by the engine combustion. They also illustrated that phases of the three lowest order components of the IAS spectrum could be utilized to identify the faulty cylinder of a diesel engine. Douglas et al [9] applied both acoustic emission and instantaneous angular speed techniques for on-line power estimation of two large marine diesel engines. They found that the calculated standard deviation of IAS waveforms in each engine cycle changes accordingly to the loading condition of the marine engines under test. The change patterns also agreed well with those of the measured acoustic emission (AE) root mean squared (RMS) energy per engine cycle at various loading conditions.

Recently, Li et al [12] presented a comprehensive discussion for optimizing IAS measurements and provided a detailed IAS error analysis. Gu et al [13] developed a theoretical model for noise reduction of IAS signals by employing a combined FFT and Hilbert transform. They then implemented the method to reduce the noise in IAS data acquisition and its influence on the IAS estimation and fault diagnosis of a rotor-shaft system.

The two most common approaches for instantaneous angular speed measurements are time/counter based method and analogue to digital conversion (ADC) based method [12]. ADC-based methods, which use only standard data acquisition equipment, are much easier to implement in practical situations than time/counter based methods. The principle of ADC based methods is to acquire analogue encoder signals from the rotating shaft where the encoder is attached and then converts the signal into digital data at a fixed sampling frequency. Thus, the IAS data can be extracted directly from raw encoder signals and the method is less likely to be affected by ambient noise. The 'zero-crossing' ADC based IAS method is employed for the diesel engine performance monitoring and is extended further for engine fault detection in this study.

The contents presented in this paper are arranged as follows: Section 2 presents a description of the test rig and the experimental setup for data acquisition and condition monitoring of a diesel engine. A 'zero-crossing' based IAS technique and a simple interpolation algorithm utilized in the study to improve the accuracy of the calculated IAS waveform are described in Section 3. This is followed by an order analysis of the IAS waveforms. Discussion and insightful comments of the results from this investigation on condition monitoring and fault detection of the diesel engine are also offered in the section. Section 4 summarizes the main findings from this study.

Diesel engine test rig and the experiment

Simulating common diesel engine faults in a controlled manner in laboratories, and characterizing the signal patterns of simulated faults at various operating conditions can provide instantaneous and accurate fault diagnosis since faults in a diesel engine do not normally occur in a short period of time. To this end, a GEP18-4 Olympian diesel engine generator set as shown in Figure 1(a) was used in the fault simulation experiment presented in this paper. The specification of the engine is described in Table 1. The diesel engine generates a nominal engine power output of about 15kW. A three-phase 15kW industrial fan heater as shown in Figure 1(b) was used to absorb the power output generated by the diesel engine generator set in the experiment. The fan heater which has three heat settings can be adjusted for various engine loadings during the test.

The sensors used in this simulation study included four resonance type (PAC Micro-30D) acoustic emission sensors, a (Kistler) high temperature pressure sensor and an (PCB) ICP piezoelectric accelerometer as shown in Figure 1. A combined optical encoder and top dead centre (TDC) recording unit taken out from the electronic distributor of a Nissan Bluebird motor vehicle was also installed onto the non-drive end of the crankshaft (i.e., opposite the flywheel) for the measurement of instantaneous angular speed and torsional vibration. The encoder has 360 circumferential evenly spaced slits (1^0 resolution) and it was assumed that the encoder was ideally manufactured with negligible manufacturing errors. The flywheel on the crankshaft reduced engine speed fluctuations, particularly at the unloaded conditions. The other sensors installed on the diesel engine test rig were used to compare their effectiveness in condition monitoring and fault detection under various simulated faults as well as to provide a comprehensive diesel engine monitoring.

A multi-channel National Instrument data acquisition card (DAQ Card-6062E) with a sampling frequency up to 500kHz, coupled with the LabVIEW software installed on a laptop computer were used for data acquisition of encoder signals in the experiment. The sampling frequency during the measurement was set at 100kHz, which was pre-determined according to the following equation to minimize the IAS measurement errors [13].

$$f_s > 4[nf_{\text{shaft}} + (n_h f_{\text{shaft}} + n\Delta f)]\ , \qquad (1)$$

where f_s is the sampling frequency, n is the number of circumferential evenly spaced slits of the encoder, n_h is the highest order of IAS components of concern, f_{shaft} is the shaft rotating frequency and Δf is the estimated shaft speed variation.

The length of each data record was 5s which encompasses about 124~130 shaft revolutions in each data file depending upon the engine loading conditions. Ten (10) data files were recorded for each engine loading at the steady state condition. These data files were used for offline averaging in the order domain during post processing of the encoder data to minimize the effect of amplitude variation and randomness on signal characterization of the diesel engine.

Instantaneous angular speed analysis

The measured encoder signal (within a small time window) of the unloaded diesel engine at the normal operating condition is shown in Figure 2(a). The measured encoder signal was used to construct the IAS waveform in the study. From the measured encoder signal, the IAS can be calculated approximately by

$$\omega(t) = \frac{\partial\varphi(t)}{\partial t} \cong \frac{\varphi_j - \varphi_{j-1}}{\Delta t_j} \quad \left(\frac{\text{rad}}{\text{s}}\right), \qquad (2)$$

where φ_j and φ_{j-1} are the crank angles of two sequential slits of the encoder, Δt_j is the time difference between the two slits.

Assuming that the encoder was ideally manufactured with evenly spaced slits in its circumference (i.e., the numerator in equation (2) equals 1^0 resolution exactly), the accuracy of IAS using equation (2) then depends purely on the measurement of the time difference Δt_j between two sequential slits. When examining the amplitude and the data point distribution of encoder pulses shown in Figure 2(a), it was found that the distribution of data point locations of each encoder pulse was slightly different from each other due to the mismatching between the sampling frequency and the crank shaft rotating speed. Therefore, there would be a non-negligible time error if the encoder signal is directly used in the IAS calculation. To improve the accuracy in estimating the time interval Δt_j between two sequential encoder pulses, a simple linear interpolation algorithm was implemented to process the encoder signal. In this implementation, an amplitude threshold value was pre-defined and the first data point on the rising edge of each encoder pulse passing this pre-defined threshold was identified. The line connecting this data point and the data point immediately prior to this point then intercepts the pre-defined threshold as shown in Figure 2(b). The time instant this line intercepts the threshold line is evaluated by using the linear interpolation algorithm, which is briefly described in the following.

After examining the data point distribution in Figure 2(a), an amplitude threshold value of $V_0 = 4\text{V}$ was chosen to minimize the time estimation error in the linear interpolation.

The locations (k) in the encoder data file where the first data point in the rising side of each encoder pulse passing this value $V(k) > V_0$ was recorded and saved in a data position vector $L(j)$ for the record of the elapse time between successive pulses. Using linear interpolation algorithm and from Figure 2(b), the approximated time instant $t_0(j)$ where each encoder pulse reaches this threshold value is:

$$t_0(j) = \frac{1}{f_s}\left[L(j) - \frac{V(k)-V_0}{V(k)-V(k-1)}\right] \quad (3)$$

Once the time instant of each encoder pulse reaching the threshold value is accurately determined, the digital form of equation (2) can be expressed by:

$$\omega(j) \cong \frac{2\pi}{n[t_0(j+1)-t_0(j)]} \quad \left(\frac{\text{rad}}{\text{s}}\right),\ j \le N-1 \quad (4)$$

where N is the length of the position vector $L(j)$.

The average shaft speed for the entire data recording length can then be determined by

$$\overline{\omega} = \frac{\sum_{j=1}^{N-1} \omega(j)}{N-1} \quad \left(\frac{\text{rad}}{\text{s}}\right). \quad (5)$$

The standard deviation of the calculated IAS waveform for the entire length of a data file is:

$$\sigma = \sqrt{\frac{1}{N-2}\sum_{j=1}^{N-1}[\omega(j) - \overline{\omega}]^2}. \quad (6)$$

The time interval of the calculated IAS waveform is no longer a constant after the linear interpolation. To enable the frequency domain analysis, the calculated IAS data is displayed in the (constant) crank angle domain (as shown in the next section). The frequency spectrum of the IAS can then be calculated by employing the fast Fourier transform as:

$$X_r(f) = \sum_{j=0}^{N-2} \omega(j)\, e^{-i2\pi\frac{jr}{N-1}}, \quad (7)$$

where r is the length of the frequency spectrum after the transform and i is the imaginary number. Note: the number of slits of the encoder (360) is used as the sampling frequency in the fast Fourier transform so that the transformation will be directly displayed in the order domain with respect to the crankshaft rotating frequency.

IAS waveform and order components at the unloaded condition

The IAS waveform of the diesel engine at the unloaded condition calculated using equation (4) in the constant crank angle domain is shown in Figure 3. It is shown that the instantaneous angular speed of the crankshaft at the unloaded condition varied from about 157 rad/s to 170 rad/s. Figure 4 shows the power spectrum of the IAS waveform displayed in the order domain. The major order components of the IAS spectrum can be correlated to major mechanical events of the diesel engine. For instance, the first major dominant order component of the IAS spectrum is attributed to the shaft rotating speed, the second order component corresponds to the engine firing frequency of the 4-stroke 4-cylinder diesel engine, while the fourth order component corresponds to the four top (or bottom) dead centres of the diesel engine per shaft revolution as a result of the change momentum of piston motions. Identification of major order components of the IAS spectrum to the mechanical events of the diesel engine is not the objective of this work. Instead, the study aims to reveal and correlate the changing pattern of the major order component of the IAS spectrum to the power output and fault diagnosis of the diesel engine.

Standard deviation per engine cycle of the IAS waveform at various loading conditions

Engine output power estimation using standard deviation per engine cycle of IAS waveforms and acoustic emission technique was investigated by Douglas et al [9] on two large marine diesel engines. In their work, they studied the change pattern of standard deviation per engine cycle of IAS waveforms at two loading conditions on one of the two test engines and three loading conditions on the other engine. They observed that the changing pattern of standard deviation per engine cycle of IAS waveforms is consistence with the changing power output of the diesel engine at the loading conditions under study. A major drawback of their work is that it did not provide a quantitative analysis or an explicit mathematical relationship to describe the power output change by the amplitude change of the standard deviation.

In this study, the standard deviation per engine cycle of IAS waveforms of the diesel engine under four loading conditions, namely, unloaded, one third load, two third load and full load, is calculated according to [9]:

$$\sigma_v = \sqrt{\frac{1}{q-1}\sum_{j=1}^{q}(\omega_j - \overline{\omega}_v)^2}\,, \tag{8}$$

where q is the length of the IAS waveform in the v^{th} engine cycle, ω_j is the IAS at the time instant t_j and $\overline{\omega}_v$ is the mean IAS for the v^{th} engine cycle.

The results are shown in Figure 5. It is observed that the amplitude of the standard deviation per engine cycle of the IAS waveform decreases as the engine loading condition increases for the first three loading conditions. This observation is consistence with the finding of Ref. [9]. However, the decreasing trend does not continue for the last loading condition when the engine was running at full load. This indicates that the standard deviation method may have limited applications in practical cases, for instance, to be used for engine loading estimation at high engine loading conditions. To overcome such limitation, an alternative method is developed in this study for diesel engine output power estimation, which is elaborated in the next section.

Correlation between the major order component of the IAS spectrum and the engine loading condition

In this section, the correlation relationship between the amplitude of the major combustion related order component of the IAS spectrum and the loading condition of the diesel engine is established. The major order component of the IAS spectrum used in the study is the second order component associated with the engine firing frequency (at twice the shaft speed). To minimize the effect of the engine speed and amplitude variations on the analysis, the IAS spectrum was averaged over the ten encoder files in the order domain for each engine loading condition, namely, unloaded (0kW), one-third load (5kW), two-third load (10kW) and full load (15kW). The averaged order component at various engine loading conditions is shown in Figure 6 for comparison. It is observed that the amplitude of this order component follows a clear exponential curve. This exponential curve can be described by the following equation:

$$\mathbf{A} = A_0 \exp^{(\alpha * \mathbf{N})}, \qquad (\mathrm{rad/s})^2, \tag{9}$$

where $\mathbf{A}$ is the amplitude vector of the power spectrum component at various engine loading conditions, A_0 is the amplitude of the IAS power spectrum component at the unloaded condition, $\mathbf{N}$ is the normalized vector indicating the loading conditions of the engine, which takes the value of 0 for the unloaded condition and 1 for the full load condition. $\mathbf{N} = \lfloor 0 \quad 1/3 \quad 2/3 \quad 1 \rfloor^T$ for the case presented in this study where T indicates a vector transpose.

The coefficient α in equation (9) can be determined by a least square curve fitting as:

$$\alpha = \frac{\mathbf{N}^T \ln(\frac{\mathbf{A}}{A_0})}{\mathbf{N}^T \mathbf{N}}, \tag{10}$$

where α =1.6873 was found for the case shown in Figure 6.

Once the relationship between the engine loading condition and the power amplitude of the order component is established, and the power amplitude of the order component at the unloaded condition is known, the power output of the diesel engine at any particular instant can be estimated by the power amplitude (A_j) of the order component of the IAS spectrum measured at that instant as:

$$N_j = \frac{1}{\alpha} \ln \frac{A_j}{A_0}, \tag{11}$$

where N_j is the normalized engine output power (with respect to the nominal engine output power) at the t_j time instant.

The trend of amplitude change of this order component (correlates to the engine firing frequency) can be explained by the effect of changing engine loading condition on the engine combustion process and the gas pressure torque. Figure 7 shows the averaged in-cylinder pressure measured at Cylinder 1 for the four engine loading conditions. It is worth noting that the data was averaged over 180 engine cycles using a time waveform event driving synchronizing averaging technique in which the averaging process was correlated and triggered by the major mechanical events of the diesel engine to overcome the difficulty of averaging quasi-periodic signals in the time domain. Figure 7 illustrates that the increase engine loading not only slightly increased the peak amplitude of the engine combustion pressure but also enlarged the area under the in-cylinder pressure curve. This implies an increase in gas pressure torque during the engine combustion when the loading increased, and thus led to the increase amplitude of the order component.

The correlation of the order component and the engine loading condition at two simulated combustion related faults

To further examine whether the changing pattern shown in Figure 6 also works for other engine operation conditions such as operating at a faulty condition, two common combustion-related faults were simulated separately in this experimental study. In one of the fault simulations, the pintle head of the injector of Cylinder 1 was partly grounded off as illustrated in Figure 8(b) to simulate a defect in the fuel spreading pattern during fuel injection of the cylinder. It is further noted that the simulated fault will not affect the fuel volume injected to the cylinder during combustion. In another fault simulation, a deep scour mark was indented onto the base and runs through the seal face of the exhaust valve of Cylinder 1 to simulate an exhaust valve leakage as shown in Figure 8(c).

It is found from Figures (9) and (10) that for both fault simulation cases, the trend of amplitude change pattern of the order component (at twice the shaft speed) also follows a similar exponential curve as revealed in the normal engine operating condition discussed in the previous section. The mathematical exponential relationship described by equation (9) can still be applied to the estimation of the engine loading condition for both simulated fault cases but with a slightly different coefficient α' and the base amplitude A_0' as:

$$\mathbf{A}' = A_0' \exp^{(\alpha' * \mathbf{N})}. \tag{12}$$

IAS analysis for diesel engine exhaust fault diagnosis

It was found that the simulated injector fault (representing an incipient injector fault) has only a very small effect on the engine combustion pressure for all engine loading conditions [14]. This finding was confirmed by the IAS analysis where the amplitude change of the second order component does not provide useful conclusive information for the diagnosis of this simulated injector fault.

On the contrary, Figure 11(a) shows that there is a substantial amplitude decrease of the second IAS order component for all engine loading conditions in the simulated leaking exhaust valve case. The decrease in amplitude of this order component compared to the corresponding case at the normal engine loading condition indicates that the valve leakage has resulted in reduced engine combustion power output. Figure 11(b) shows that the amplitude difference between the normal and the faulty cases increases as the engine loading condition increases. This implies that the power loss due to the leaking exhaust valve increases for higher engine loading. The finding is confirmed by the calculated peak amplitude of the gas pressure torque from the measured in-cylinder pressure of Cylinder 1 for the normal and the faulty cases at various loading conditions as shown in Figure 12. This figure also illustrates that the effect of the leaking exhaust valve on the gas pressure torque produced by the combustion of the cylinder is relatively small at the unloaded condition. The effect increases progressively as the engine loading increases due to the leakage of higher pressure gas to provide power for higher loading during combustion.

Conclusions

In this paper, an instantaneous angular speed analysis technique was presented for the estimation of engine power output and condition monitoring of diesel engines. It was shown that IAS analysis can provide useful information about engine speed variation caused by the changing piston momentum and crankshaft acceleration and can also be used for engine power output estimation at various engine operating (either normal or faulty) conditions. It was found that the method of standard deviation per engine cycle of an IAS waveform [9] can only be employed to estimate the diesel engine power output at low loading conditions.

The low frequency order components of the IAS spectrum of a diesel engine can be traced back to major mechanical events of the diesel engine. In particular, it was found in this study that the changing amplitude of the second order component of the IAS spectrum corresponding to the engine firing frequency follows a clear exponential curve to the changing engine loading conditions. This trend can be explained by the fact that the amplitude of this order component is directly associated with the engine combustion process and the gas pressure torque whose amplitude also increases with increase engine loading conditions. A mathematical relationship was established in the study for the in-situ estimation of the engine power output based on the changing amplitude of this order component of the IAS spectrum. The revelation of the correlation relationship between this order component and the engine loading condition as well as the mathematical model established in this work, can be employed for engine loading monitoring in practical applications.

In addition to being used for the estimation of engine loading conditions, IAS analysis can also be employed for condition monitoring and fault detection of combustion related faults in a diesel engine. It was illustrated in this study that the amplitude of the order component of IAS spectra corresponding to the engine firing frequency in the leaking exhaust valve case is substantially less than that of the normal engine operating case for the same loading condition. The increased amplitude difference of this order component between the normal and the faulty cases revealed the increase in power loss of the engine due to the leaking exhaust valve as the load increased.

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References

1. Feldman M and Seibold S. Damage diagnosis of rotors: application of Hilbert transform and multihypothesis testing. *J Vib Control* 1999; 5: 421-442.
2. Remond D. Practical performances of high-speed measurement of gear transmission error or torsional vibrations with optical encoders. *Measurement Sci Tech* 1998; 9: 347-353.
3. Stander CJ and Heyns PS. Instantaneous angular speed monitoring of gearboxes under non-cyclic stationary load conditions. *Mech Sys Signal Proc* 2005; 19: 817-835.
4. Du S and Randall RB. Encoder error analysis in gear transmission error measurement. *Proc IMechE Part C: J Mech Eng Sci* 1998; 212: 277-285.
5. Sweeney PJ and Randall RB. Gear transmission error measurement using phase demodulation. *Proc IMechE Part C: J Mech Eng Sci* 1996; 210: 201-213.
6. Yang J, Pu L, Wang Z, Zhou Y and Yan X. Fault detection in a diesel engine by analysing the instantaneous angular speed. *Mech Sys Signal Proc* 2001; 15: 549-564.
7. Charles P, Sinha JK, Gu F, Lidstone L and Ball AD. Detecting the crankshaft torsional vibration of diesel engines for combustion related diagnosis. *J Sound Vib* 2009; 321: 1171-1185.

8. Taraza D, Henein NA and Bryzik W. The frequency analysis of the crankshaft's speed variation: a reliable tool for diesel engine diagnosis. *ASME J Eng for Gas Turbines and Power* 2001; 123: 428-432.

9. Douglas RM, Steel JA, Reuben RL and Fog TL. On-line power estimation of large diesel engine using acoustic emission and instantaneous crankshaft angular velocity. *Proc IMechE Int J Eng Res* 2006; 7: 399-410.

10. Sasi AYB, Gu F, Payne B and Ball A. Instantaneous angular speed monitoring of electric motors. *J Quality in Maintenance Eng* 2004; 10: 123-135.

11. Renaudin L, Bonnardot F, Musy O, Doray JB and Remond D. Natural roller bearing fault detection by angular measurement of true instantaneous angular speed. *Measurement Sci Tech* 2010; 24: 1998-2011.

12. Li Y, Gu F, Harris G, Ball A, Bennett N and Travis K. The measurement of instantaneous angular speed. *Mech Sys Signal Proc* 2005; 19: 786-805.

13. Gu F, Yesilyurt I, Li Y, Harris G and Ball A. An investigation of the effects of measurement noise in the use of instantaneous angular speed for machine diagnosis. *Mech Sys Signal Proc* 2006; 20: 1444-1460.

14. Lin TR, Tan ACC and Mathew J. Condition monitoring and diagnosis of injector faults in a diesel engine using in-cylinder pressure and acoustic emission techniques. In: *Proceedings of the 14th Asia Pacific Vibration Conference* (ed S Law et al), Hong Kong, P. R. China, 5-8 December 2011, pp. 454-463.

Figure Captions

Figure 1. Graphical illustration of the diesel engine test rig and sensors; (a) the test rig; and (b) the industry fan heater.

Figure 2. (a) Raw encoder signal at the engine unloaded condition; and (b) Graphical illustration of the linear interpolation.

Figure 3. Time waveform of the calculated instantaneous angular speed at the unload condition.

Figure 4. Power Spectrum of the IAS waveform at the unload condition.

Figure 5. Standard deviation per engine cycle of IAS signals at various engine loading conditions.

Figure 6. Power spectrum amplitude of the order component corresponding to the engine firing frequency (twice the shaft speed).

Figure 7. Comparison of the averaged in-cylinder pressure of Cylinder 1 at various loading conditions.

Figure 8. Simulated combustion related faults; (a) Normal injector head; (b) Pintle head partly grounded off; and (c) Leaking exhaust valve.

Figure 9. Power spectrum amplitude of the order component corresponding to the cylinder firing frequency at the faulty injector case, $\alpha = 1.02$.

Figure 10. Power spectrum amplitude of the order component corresponding to the cylinder firing frequency at the leaking exhaust valve case, $\alpha = 1.58$.

Figure 11. (a) Comparison of the power amplitude of the 2X order component between the normal and faulty exhaust valve cases at various engine loading conditions; and (b) The amplitude difference of the order component between the normal and faulty exhaust valve cases as the engine loading increases.

Figure 12. Comparison of the peak amplitude of the gas pressure torque produced by Cylinder 1 of the normal and the leaking exhaust valve cases at various loading conditions.